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GODDARD SPACE FLIGHT CENTER
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MAGNETIC FIELD AND ELECTRON OBSERVATIONS NEAR THE MAGNETOPAUSE*

by

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Extensive magnetic field observations have been made of magnetopause crossings by satellites and space probes (Heppner et al., 1963; Cahill and Amazeen, 1963; Ness et al., 1964, Ness, 1965; Holzer et al., 1966; Heppner et al., 1967; Fairfield and Ness, 1967; Ness, 1967; Behannon, 1968). Identifications of the magnetopause have also been made by plasma measurements (Bridge et al., 1965; Wolfe et al., 1966; Gosling et al., 1967; Vasyliunas, 1968a). Although these plasma observations indicated sudden changes in the plasma characteristics across the boundary, their time resolutions were not adequate to study the structure in the boundary layer. In the electron plasma measurement on OGO-5 to be discussed in this paper the time required for one cycle of observation is approximately 23 seconds, and this high resolution has made it possible to investigate the changes in the plasma parameters across the boundary in more detail than has been possible in the previous studies.

The observed average shapes and positions of the magnetopause have previously been found to be in gross agreement with theoretical results based on gas dynamical models (Ness, 1967; Heppner et al., 1967; Gosling et al., 1967; for theoretical models: e.g., Spreiter and Briggs, 1962 a,b; Midgley and Davis, 1963; Mead and Beard, 1964; Spreiter et al., 1966; Dryer and Faye-Petersen, 1966). In these theoretical models the solar wind pressure, represented in different ways in different models, is balanced by the magnetic pressure inside the boundary, altogether ignoring the plasma pressure inside it. However, there is increasing evidence for the presence of plasma inside the magnetopause based on observations of magnetic field

behavior (Heppner et al., 1967; Sugiura et al., 1970) and on direct measurement of plasma (Frank and Shope, 1967; Vasyliunas, 1968b). Observational study of the pressure balance across the magnetopause is obviously needed. The structure of the boundary layer is not well understood at present. A theoretical treatment has recently been carried out by Eviatar and Wolf, (1968) who conclude that an unstable boundary approximately 100 km thick would be sufficient to provide the viscous forces to drive, for example, the Axford-Hines magnetospheric convection model.

In this paper several examples of magnetopause crossings are shown with OGO-5 electron plasma and magnetic field data; a diagnostic study of the magnetospheric boundary using high time resolution magnetic field and 45 eV electron flux measurements, and typical changes in some of the plasma parameters across the magnetopause are presented. The pressure balance across the boundary is investigated, and the significance of plasma inside the boundary is pointed out.

Experimental

Observations of electron flux as a function of energy were made with the GSFC triaxial spectrometer (Lind and McIlwraith, 1965). This device, which was mounted on the -Z face of the main body of the satellite OGO-5, has three cones of sensitivity, mutually at right angles, with the normal to the -Z face making equal angles with each detector axis, Figure 2. The directions of the detectors were fixed in satellite coordinates, and so the axes made angles with the magnetic field which varied along the orbit. Electrons entering each detector were accelerated by falling through a potential difference of 100 volts, analysed in energy by a 127 degree electrostatic analyser and recorded by a channeltron electron multiplier. The preacceleration procedure had the effect of increasing the absolute width of the energy pass band at low energies. This pass band ΔE at energy E is given by the relation $\Delta E = 0.16\ (E+100)$, E in electron volts. Thus for example, the pass band at a nominal 45 ev was from 33.5 to 56.5 ev. The analysers were stepped through an energy range 10ev to 9.9 kev in fifteen steps, at the satellite telemetry frame rate of 1.15 seconds per step. The fifteen steps, calibration step, and exponential return to zero energy took a total of 23 seconds. The calibration was accomplished by means of a radio-active Ni^{63} source, the electrons from which were progressively attracted away from the detector as the potentials applied to the analyser plates were increased. There was thus a correction to be applied to readings taken on the low energy steps, where the natural flux was normally large, but essentially no correction to the higher steps where the natural flux was small.

The detectors were operated in an analog mode, in which the potential across the electron multipliers was varied to keep the output current constant at 3×10^{-9} amperes. The telemetered signal was proportional to the multiplier potential, which was related in an approximately inverse logarithmic way to the incoming electron flux. The detectors were sensitive to a minimum flux of approximately $10^5/cm^2/sec/sterad/kev$, and had a dynamic range of greater than $10^5:1$.

This analog system turned out to be ill advised as the relatively large current drawn from the multipliers proved to induce accelerated degredation. The life of the experiment was thereby reduced to about 30 days, but during that time it operated in a very satisfactory manner, providing observations of the electrons in the solar wind, magnetosheath, and magnetosphere.

The magnetic field data used in this paper were obtained by a triaxial fluxgate magnetometer, which is an improved version of those flown on OGO's 1 and 3 (Heppner et al., 1967; Sugiura et al., 1968; Ledley, 1969). With a digitally controlled field compensation system the range of measurement is $\pm$ 4,000γ (gamma) with a digital resolution of $\pm 1/8\gamma$. The sampling rate is 0.868, 6.94, or 55.55 times per second for the three optional rates of 1, 8, or 64 kilobits per second, but the present study is based on sampled data from 8 kilobit records. This sampling was carried out by choosing the reading taken at the time closest to a given second.

The plasma flux observations represent averages taken over a period of 1.15 seconds, during which five individual observations were made. For any given differential energy interval, these average

observations are separated by the cycle time of 23 seconds. This is also the time duration required to obtain an electron spectrum. Changes taking place in less than this time will not be correctly reflected in spectral changes or, therefore, be reflected in the density or temperatures derived from such spectra.

The density and temperatures plotted and used in the calculations that follow are derived by fitting the flux data to a stationary isotropic Maxwellian of the form

$$\text{Flux} = \frac{\text{counts}}{\text{cm}^2/\text{sec/sterad/kev}} \simeq \left[\frac{2n_e^2}{m_e(\pi kT_e)^3}\right]^{\frac{1}{2}} \cdot E \cdot \exp\left(-\frac{E}{kT_e}\right) \quad (1)$$

This is done by a least squares technique, which exploits the fact that

$$\ln\left[\frac{\text{Flux}_i}{E_i}\right] = A(n_e, T_e) + B(T_e)E_i \quad (2)$$

where the E_i used are 25, 45, 80, and 130ev. This technique yields A and B from which T_e and n_e may be straightforwardly calculated. The form of equation 1 is derivable from the convected isotropic Maxwellian which would be more rigorously correct to describe an isotropic Maxwellian distribution in a frame moving with a bulk speed U, as observed from the relatively stationary frame of the satellite. The approximation is a good first order one since the bulk speed U<250 km/sec, even in the sheath, while the thermal speeds v are of the order 3000 km/sec, making U/v <0.1.

Description of Observations

a). Quiet Conditions.

In Figure 1 we see an example of a magnetopause crossing which occurred between 0217 and 0230 UT on March 10, 1968. Reading from the top, the two angles, solar ecliptic longitude ϕ_{SE}, and latitude θ_{SE}, which define the direction of the magnetic field vector in solar ecliptic coordinates, and its magnitude B are plotted. In the lowest graph, to the same time scale, the observations of the individual analysers of the 3 axis electron spectrometer are denoted by a dot, a cross, and a triangle respectively. The observations representing the electron flux in the energy range 53.5 to 56.5 ev are spaced at intervals of 23 seconds, since each differential energy channel is sampled once for every spectrometer cycle.

Observations in the magnetosphere are shown on the left, and observations in the sheath on the right; the increased flux there represents electrons heated in the sheath by energy dissipated by the solar wind in traversing the earth's bow shock. It is clear that between 8420 secs and 8630 secs the magnetopause transition occurs. The large changes in direction and magnitude of the magnetic field are associated with the change in the electron flux measured by all three detectors of approximately one and a half orders of magnitude. This indicates no marked departure from isotropy on either side of the boundary. The magnetic field and particle detector directions are shown in Figure 2.

There are five observations in the rising part of the lowest graph in Figure 1, indicating that the flux change occupied a time of approximately

115 secs. The magnetic field changes take place in about 200 seconds. If the magnetopause is assumed at rest and the satellite speed is taken to be approximately 1 km/sec, we obtain a minimum boundary thickness of 100 to 200 km.

In Figure 3 we see observations, displayed in the same way as those in Figure 1, of a magnetopause crossing made between 1240 and 1250 UT on March 7, 1968. The angles ϕ_{SE} and θ_{SE} show similar changes here to those observed in Figure 1, ϕ_{SE} going from ~100 degrees to ~270 degrees, and θ_{SE} from 10 degrees to -30 degrees. The electron flux change is amaller (~10 times) and takes place in a shorter interval of time than on March 10, though there are disturbances lasting for about 100 secs in the magnetic field parameters. In this case the magnetic field in the magnetosheath is lower than in the magnetosphere, the magnitude reaching its quiescent value at about 45930 secs. The magnetosheath field magnitude in Figure 1 also shows a quiescent value of about 35 gamma, reached at 8630 secs, in this case higher than in the magnetosphere. The angular relationships between magnetic field and detector axes on March 7 are shown in Figure 2. These typical combined observations at relatively quiet times thus strongly suggest a boundary which, if at rest, has a thickness between 100 km and 200 km.

b. Disturbed conditions.

As an example of a more complicated situation, we now discuss observations made on March 17, 1968. During this period, the satellite was outbound, moving between a radial distance of $11.3R_e$ at 2010 UT and $15.8R_e$ at 2400 UT. A plot of the flux measured by two detectors of the electon spectrometer is shown in Figure 4. A very clear example of a crossing at 2313 UT from the magnetosphere to the sheath is indicated, together

with the corresponding magnetic field observations. It will be seen that this is qualitatively very similar to those discussed above. A momentary excursion from the magnetosphere into the sheath and back also took place at 2105 UT, and is also illustrated in Figure 4. At that time the recorded electron flux showed a short lived increase from the value of between 10^7 and 10^8/cm^2/sec/sterad/kev characteristic of the magnetosphere, to the value of 1.5×10^{10}/cm^2/sec/sterad/kev recorded in the sheath later in that day.

Although many variations are observed in both sets of data between 2105 and 2313 UT, comparison indicates there are no other magnetopause crossings. The combination of magnetic field and low energy electron observations form a good diagnostic method for the identification of magnetopause traversals.

The flux data have also been fitted to a stationary Maxwellian velocity distribution, as discussed above. An example of the results for the period 2000 to 2400 UT on March 17, 1968, are shown in Figure 5. This covers the radial distance 11 R_e to 13.8 R_e inclusively. Inside the magnetosphere, until about 2100 UT, the densities are very small, of order 1 cm^{-3}. The very close correspondence between the results for all three axes should be noted. At about 2105 UT the abrupt increase, which is described above, occurred in all three detectors, and the clear magnetopause crossing at 2313, also described above, can be seen, after which the satellite remained in the magnetosheath where the electron density was 20 cm^{-3}. This diagram is consistent with our picture of a thin magnetopause boundary moving slowly over a radial range of about two earth radii.

Data for a more disturbed period (K_p=4) are shown in Figure 6. There the electron densities, observed by the three detectors of the electron

spectrometer, are shown for the period 0410 to 0617 UT on March 15, 1968. From 0539 onward all three detectors indicated densities of order 30 cm^{-3} characteristic of the magnetosheath, and before 0418 UT densities of order 1 cm^{-3} characteristic of the magnetosphere when observations are made at an energy above 25 ev. At approximately 0418:30 UT a momentary density increase was observed in all three detectors. Correlating this with simultaneous magnetic field observations, it appears that the spacecraft made a penetration into the sheath at this time. Since the electron fluxes may be changing during the time of one spectral scan, the maximum value of density deduced does not necessarily reflect the true magnitude of the fluctuation. The density increase observed at about 0441:40 UT (marked C in the diagram) corresponds to a disturbance in the magnetic field, but is not clearly a transition. The next definite transition occurs at 0510:30; in between this time and 0529 several transitions occur, leaving the spacecraft in the magnetosphere until approximately 0524:45 UT when it enters the sheath. After a transition back to the magnetosphere at about 0534, the spacecraft makes another transition back to the sheath, 0537:30, where it remains until entering the interplanetary medium. As can be seen from the density fluctuations, the magnetosheath was very disturbed on this day, and it would appear that the magnetosphere adjacent to the boundary was also disturbed. The boundary appeared to be in motion, with an amplitude of order $\pm 1\ R_e$.

Discussion

It can be readily seen from the figures that the behavior of the electron flux at 45 ev forms a valuable diagnostic for the detection of magnetopause crossings. Detailed studies of the nature of the magnetopause require that accurate identification be made of crossings. This is difficult using the magnetic field alone, and it is precisely these difficult cases which are often of considerable interest. The observations made here are of limited angular resolution, since only three small solid angles are sampled. Although approximate isotropy is indicated, in a future study this is a parameter which could with advantage be covered in more detail.

In support of the identifications made in the diagrams, it is generally noted that the flux of electrons with energies of order 1 kev decreases simultaneously with the increase in flux of 45 ev electrons as the satellite goes from the magnetosphere to the sheath. It appears that, at least at quiet times, electrons of 1 kev energy are trapped, or quasi-trapped, in the outermost parts of the magnetosphere. It has been shown that the flux of electrons of higher energies (79 kev) undergoes a marked decrease, indicating a cessation of trapping at these transitions (Ogilvie et al., 1969).

The high time resolution observations shown in Figures 1 and 3 show that the large angular changes in the magnetic field direction, corresponding to the transition from the magnetospheric field to the interplanetary field modified by passage through the earth's bow shock, and illustrated in Figure 2, take place after the change in plasma flux. Thus the "boundary layer" separating the two regions, which might be identified with an unstable region

such as that described by Eviatar and Wolf (1968), has a magnetic field configuration like that of the magnetosphere, but an electron population similar to that of the magnetosheath. Mixing of the two plasma populations in this region, one from the magnetosphere and one from the sheath at a much higher temperature, may be important in the mechanism of instability in the boundary.

Figures 5, 6 and 7, which show three representative electron density variations observed during traversals of the region of the magnetopause, are interpreted as showing that although the magnetopause is sometimes at rest, Figure 7, or more accurately moving slowly with respect to the spacecraft, it often moves around over a mean distance of order ± 1 R_e. Thus the satellite encounters it several times, Figures 5 and 6 ; its mean speed is perhaps several times that of the satellite, 1.5 km/sec . Fine detailed correspondence is seen between the three detectors in Figures 5, 6 and 7, indicating that this interpretation of multiple traversals is correct, and that the more disturbed readings, in which large fluctuations are observed, do correspond to fluctuations in the electron density. It should be noted that a spectrum takes 20 seconds to aquire, and that observations at the same energy are made at 23 second intervals. Thus considerable smoothing has been introduced, for example, into the data of Figure 5 by the operation of the instrument.

Considering the high resolution data for the "quieter" crossings, such as Figure 3, we see that the changes in $\overline{B}$ and flux occupy a total time duration of ~100 seconds. Thus, assuming that the satellite speed is large compared with any residual motion of the boundary layer, and that it crosses the latter at a large angle to its surface, the thickness is ~150 km. This is of the same order as envisaged by Eviatar and Wolf (1968)

and others.

The value of the quantity $\beta = \frac{nkT}{B^2/8\pi}$

may be estimated by performing a pressure balance calculation across the magnetopause. We write the equation

$$\frac{B'^2}{8\pi}(1+\beta) = \frac{B_s^2}{8\pi} + n_s k\, T_s(1+f) \qquad (3)$$

where B' is the magnetic field in the magnetosphere and B_s that in the sheath, and the factor f represents the ratio of the proton temperature in the sheath to T_s, the electron temperature there.

We can only obtain order of magnitude results, since our values of T_s, n_s, are characteristic only of the electron population down to an energy of 25 ev; although observations are made at 10 ev we consider this to be too close to the probable satellite potential energy for them to be reliable. It is nonetheless interesting to see if the value of β we obtain is of order unity, a value which divides the parameter regime between the field dominated and plasma dominated conditions.

For the value of f we adopt 2.5 based upon observations in the foreward hemisphere of the magnetosheath by Wolfe et al., 1967 and Montgomery et al., 1968. Equation 3 ignores dynamic pressure; this is valid here because of the angular distance from the subsolar point at which the measurements were made, Table I. At these angles and very close to the boundary surface the flow direction is parallel to the boundary.

In Table I we see a tabulation of the parameters and the corresponding calculated values of β in the magnetosphere adjacent to the boundary;

though not of high precision, these values in most cases are of order unity. There appears to be a tendency for the highest values of β to be associated with the quietest conditions. The high values of β we calculate would imply rather high densities in the far magnetosphere of 10 to 100 cm^{-3}, if the temperature there is 10^5 to 10^4 degrees. However, a considerable contribution to β might be made by high energy particles. Heppner et al. (1967) and Sugiura et al. (1970) have found a low field-gradient region near the geomagnetic equator at distances between about 11 R_e and the magnetosphere, and interpreted this observation to imply a presence of plasma of $\beta \sim 1$. Vasyliunas (1968b) has observed intense low energy electron fluxes near the magnetopause on the morning side, where the observations discussed in the present paper were made, also favoring high values of β in this region. The present discussion refers to the morning side of the magnetosphere and the possibility of a dawn-dusk asymmetry in the magnetopause pressure balance is likely.

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TABLE I

Date Approx. Time U.T. 1968	Distance from Sub-Solar Point Degrees	B' γ	B_s γ	N_s cm^{-3}	T_s 10^5 °K	$(1+\beta)$*	σ
March 7	62.5						
1243		20	30	6	3	2.79	0.27
March 10	68.4						
0220		22.5	35	26	2.4	3.91	0.74
March 15	85.5						
0418		40	52	1.3	4.0	1.73	0.01
0510		48	28	19.6	5.4	0.[illegible]9	0.27
0524		38.5	18	29.2	4.3	1.24	0.51
0534		38.5	13.6	25.4	3.1	0.76	0.32
0537		28.9	11.0	21.1	5.3	1.77	0.81
March 17	75.3						
2105		37.7	23.3	12	5	0.89	0.25
2313		30	30	14	4.8	1.90	0.45
March [illegible]	81						
1747		29	22	16.5	3.5	1.40	0.41
					Average	1.73	

*The precision of the quantity $(1+\beta)$ depends primarily upon values of n_s, which are not known absolutely to better than ±50%. The value of σ which is given in column 8 is the variation of $(1+\beta)$ using this uncertainty. Although three of the values of $(1+\beta)$ above are less than unity, and clearly not correct, when the uncertainties in n_s are taken into account β is always consistent with being >0.

FIGURE CAPTIONS

Figure 1 The upper part of the diagram shows ϕ_{SE}, θ_{SE} and B for the period 2:17:40 to 2:29:40 UT on March 10, 1968. The lower part shows differential electron flux at 45 ev for the same period.

Figure 2 These diagrams show the relationship between the directions of sensitivity of the three detectors and the solar direction and those of the magnetic field before and after the traversal of the magnetopause.

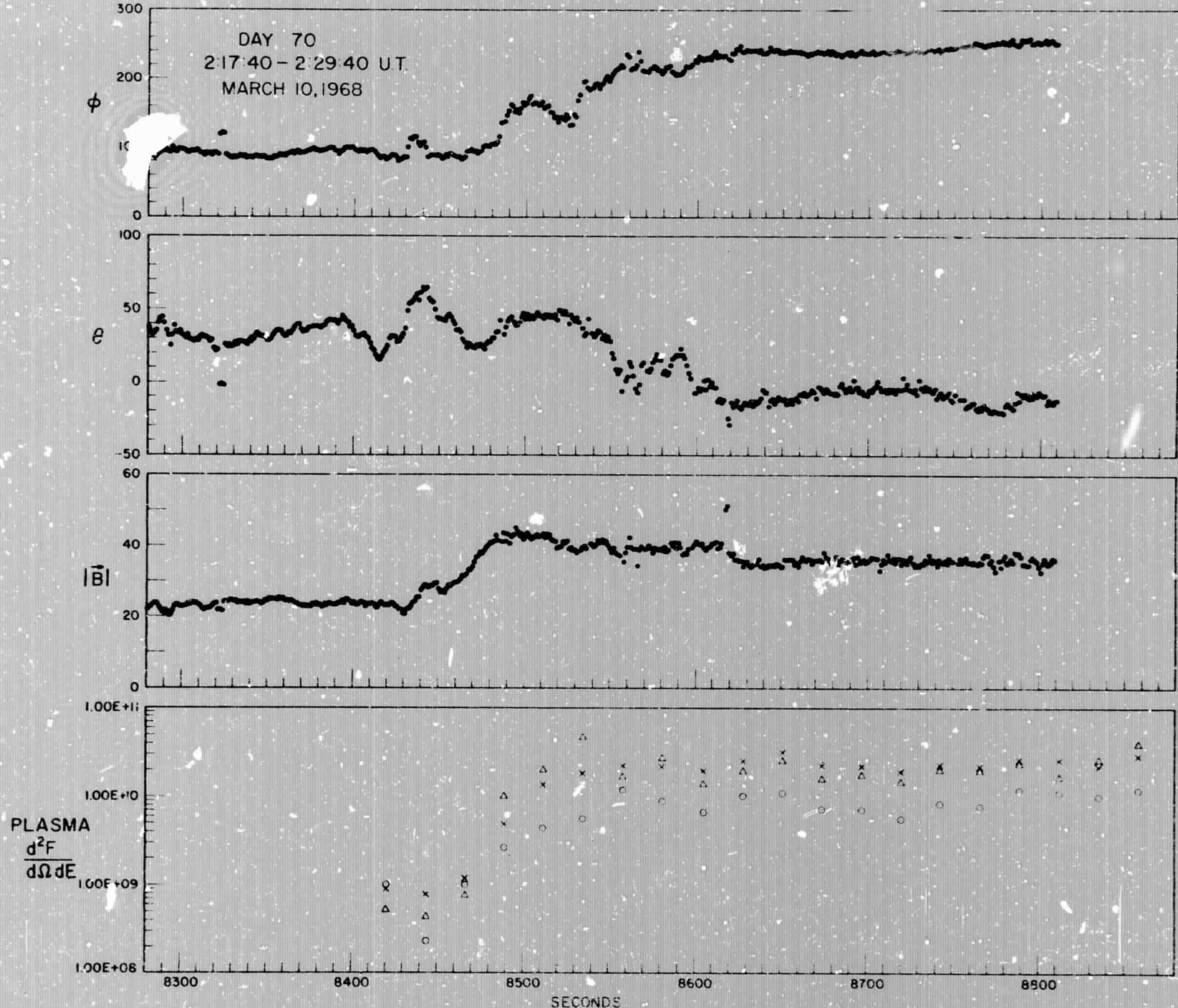
Figure 3 Magnetic field and electron flux for the period 12:40 to 12:50 UT on March 7, 1968.

Figure 4 Electron flux as observed by two detectors between 2000 and 2400 UT on March 17, 1968. Magnetic field observations are shown inset to a larger scale.

Figure 5 Electron density observations derived from 25 ev, 45 ev, 80 ev, and 130 ev flux observations from 2000 to 2400 UT on March 17, 1968 showing several magnetopause crossings.

Figure 6 Electron density for the period 0410 to 0615 UT on March 15, 1968. Several magnetopause crossings are seen, starting after 0510 UT.

Figure 7 Electron density observations from 1200 to 1345 UT on March 7, 1968. A Single crossing of the magnetopause is seen.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MARCH 10,1968
φ
θ
|B|
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d²F/dΩdE
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200
0
100
50
0
-50
60
40
20
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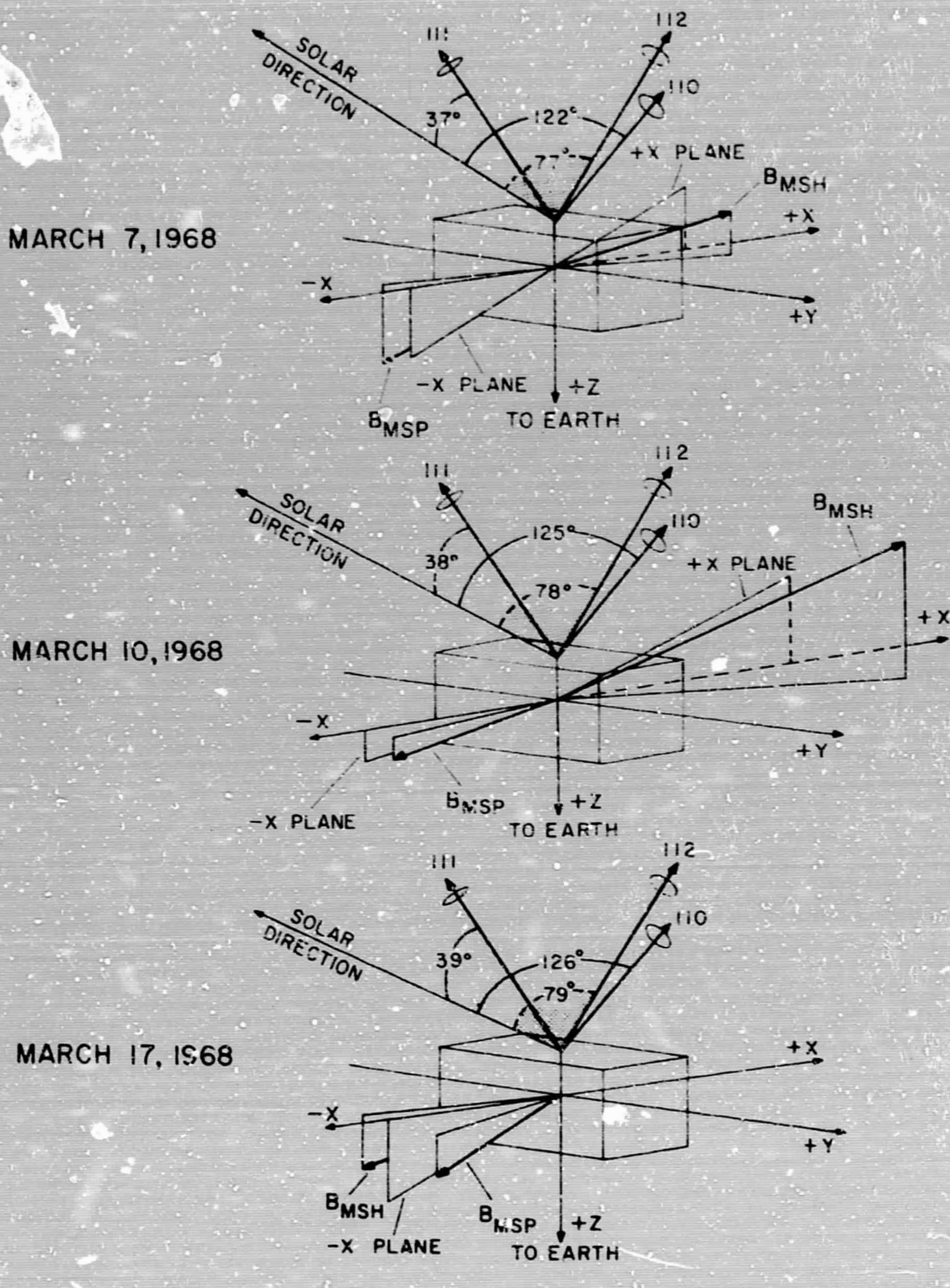
8600
8700
8800

Figure 1


MARCH 7, 1968
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112
110
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122°
77°
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B MSH
+X
-X
+Y
-X PLANE
+Z
TO EARTH
B MSP
MARCH 10, 1968
SOLAR DIRECTION
111
112
110
38°
125°
78°
+X PLANE
B MSH
+X
-X
+Y
-X PLANE
B MSP
+Z
TO EARTH
MARCH 17, 1968
SOLAR DIRECTION
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TO EARTH

Figure 2

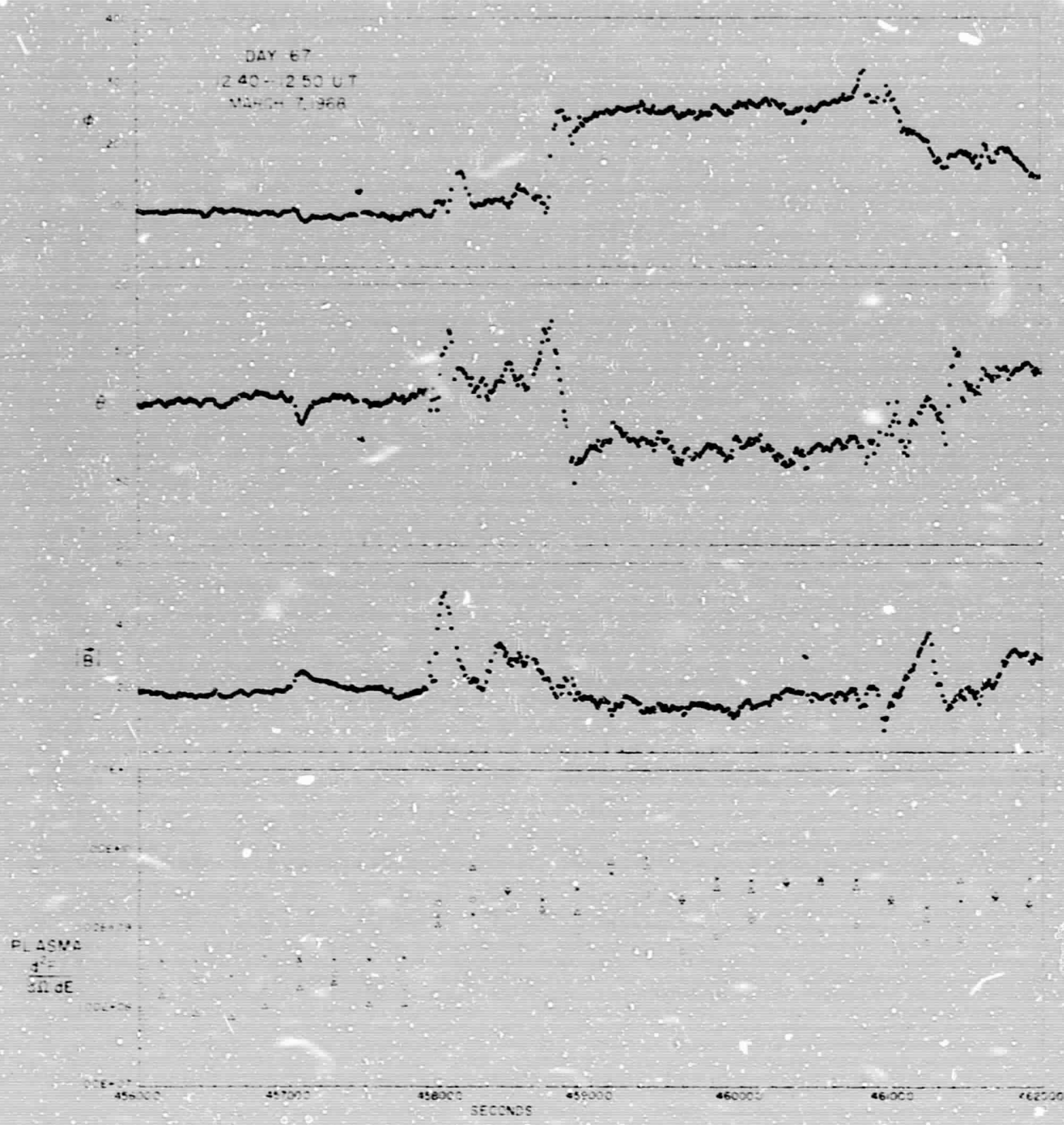
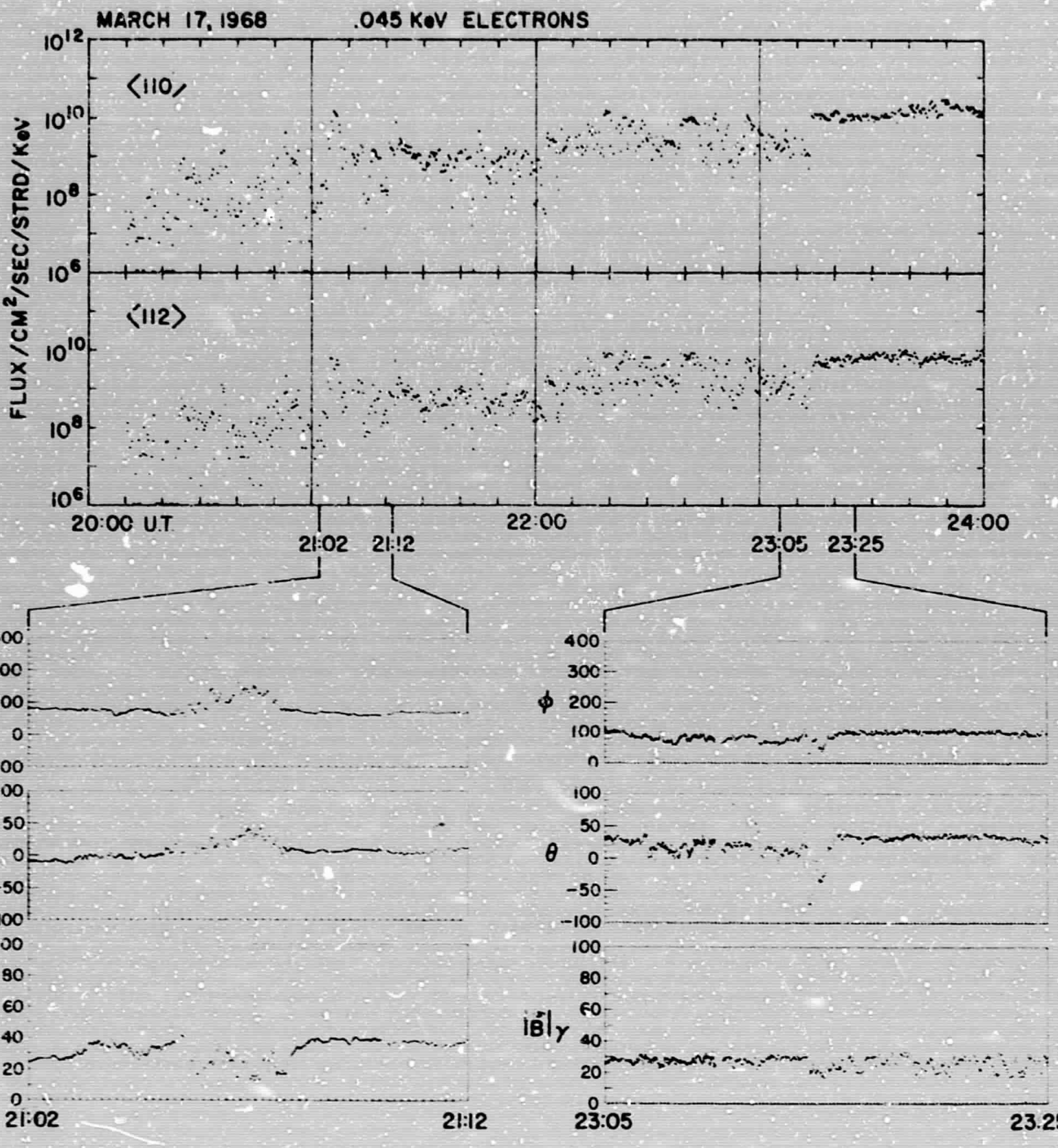


Figure 3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⟨112⟩
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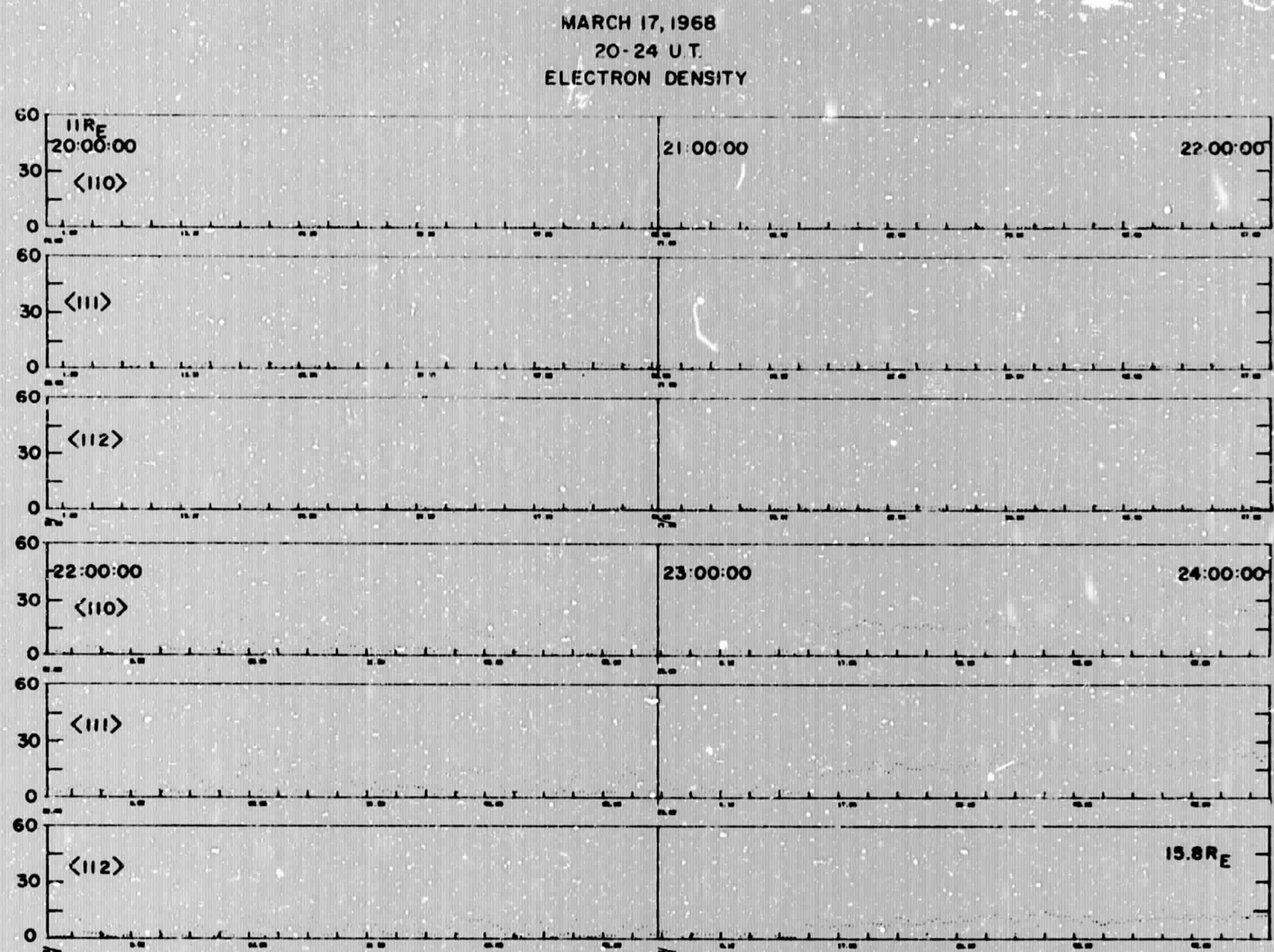
21:02
21:12
22:00
23:05
23:25
24:00
φ
θ
|B|γ

Figure 4


MARCH 17, 1968
20-24 U.T.
ELECTRON DENSITY
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21:00:00
22:00:00
23:00:00
24:00:00
⟨110⟩
⟨111⟩
⟨112⟩
60
30
0
$15.8R_E$

Figure 5

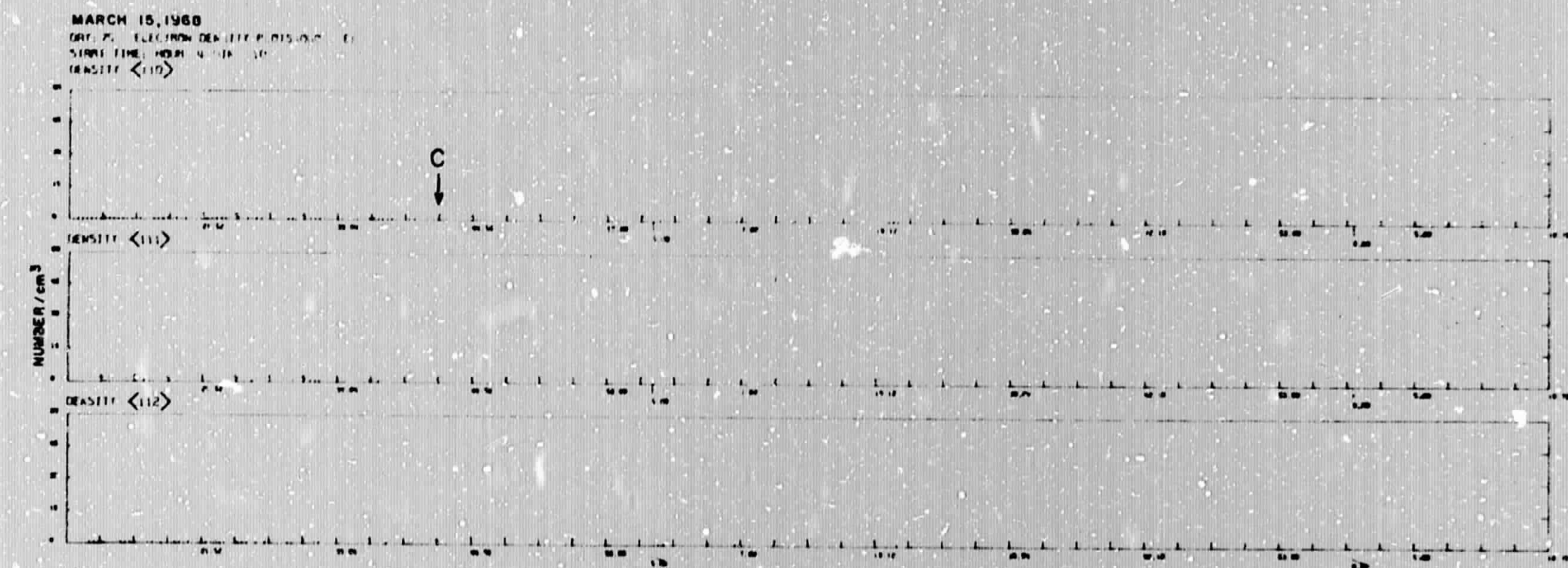
MARCH 15,1968
DENSITY <110>
C
DENSITY <111>
NUMBER/cm^3
DENSITY <112>

Figure 6

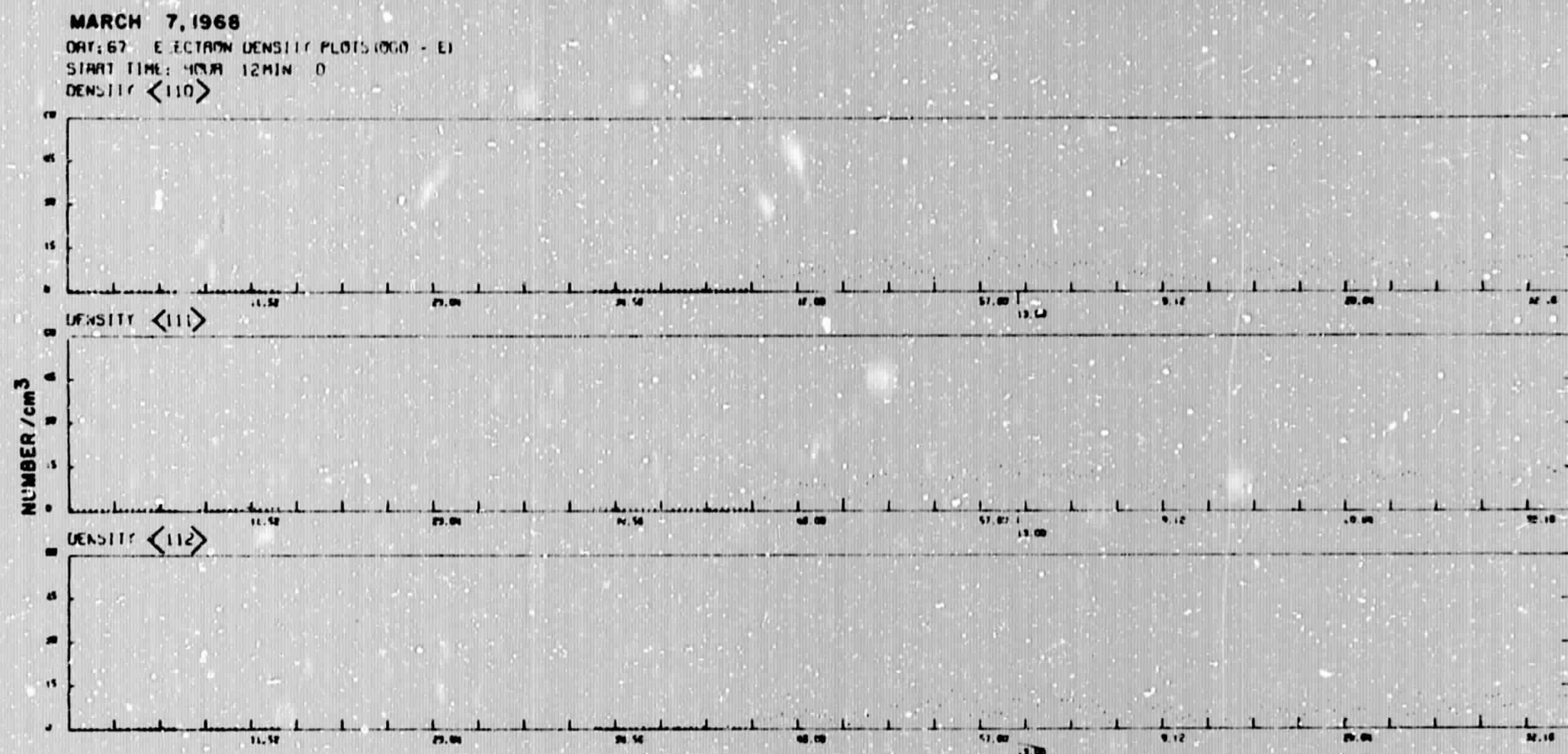
MARCH 7, 1968
ORT: 67 ELECTRON DENSITY PLOTS (OGO - E)
START TIME: 4HOUR 12MIN 0
DENSITY <110>
DENSITY <111>
DENSITY <112>
NUMBER/cm3

Figure 7

END

DATE

FILMED

JUL 21 1970